Electronics for Physicists

Analog Electronics

Chapter 8; Lecture 15

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Institute for Data Processing and Electronics

Chapter 8

Additional Topics

- Filters and Voltage Regulators
- Noise

Noise

In: Chapter 8 - Additional Topics

- From a detector perspective

Based on H. Spieler, N. Wermes

Types of Noise

- Distinguish different types of noise:
  - Signal noise (better: signal fluctuations)
  - Electronic noise

inherent to a system

  - EMI (electromagnetic interference)
    RFI (radio frequency interference)
    “pick-up noise”

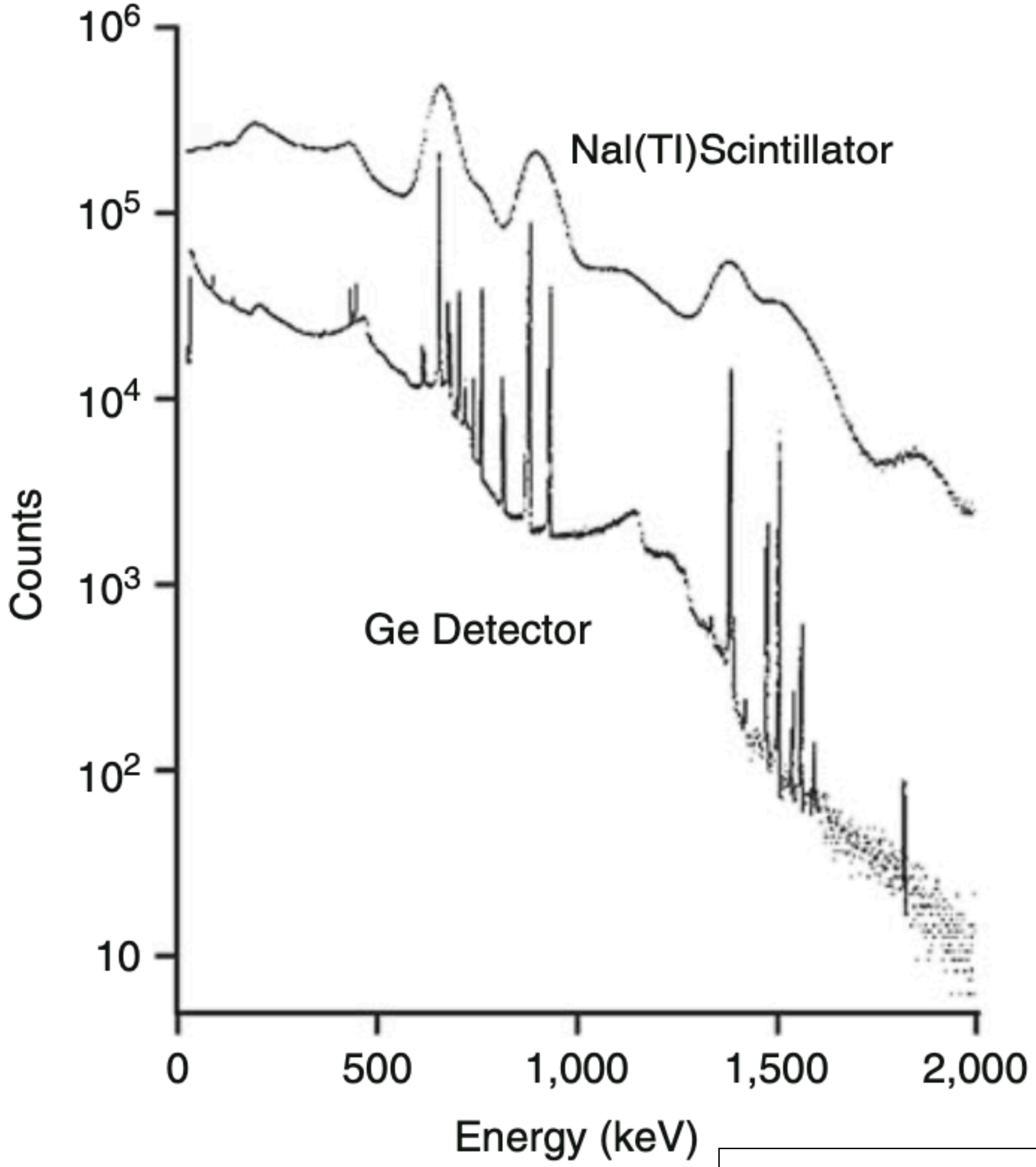
    Often: common-mode noise

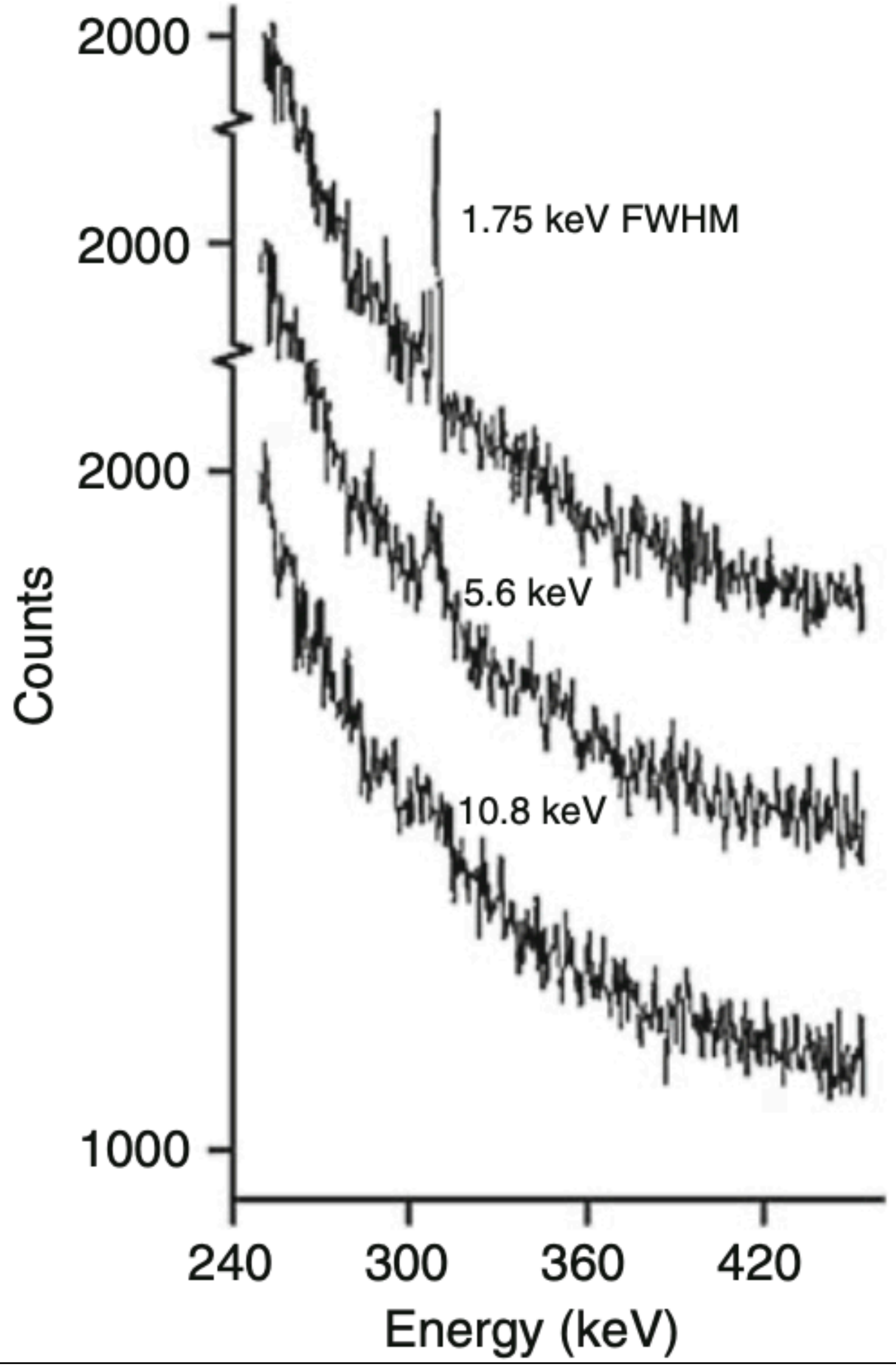
introduced externally

different for every system - often depends on (changing) external conditions

Why should you care?

Effect on detector signals





Lower noise improves:

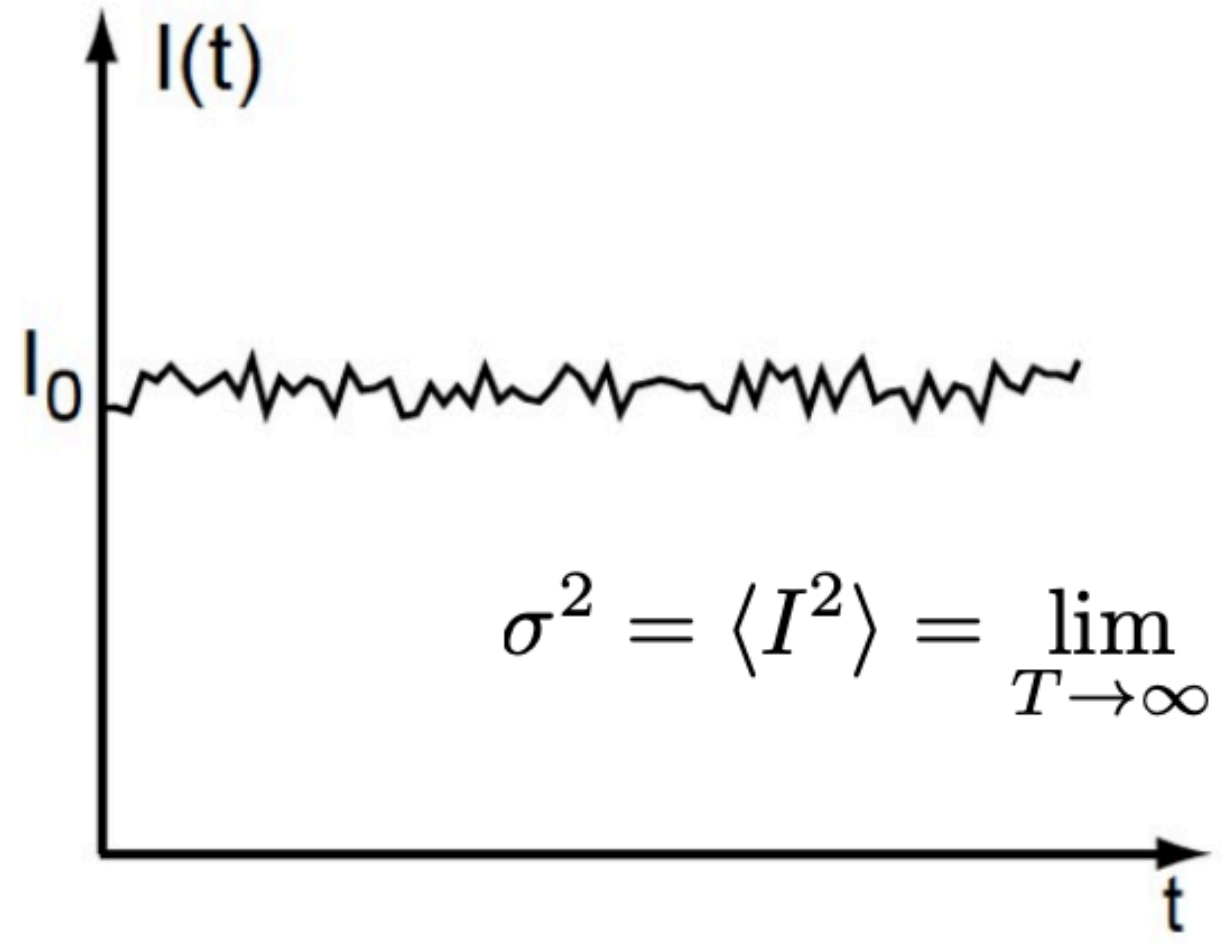
- resolution and ability to distinguish signals
- signal-to-noise ratio

Aus: H. Spieler, in I. Fleck et al. (eds.), Handbook of Particle Detection and Imaging, Springer (2020)

Quantifying Noise

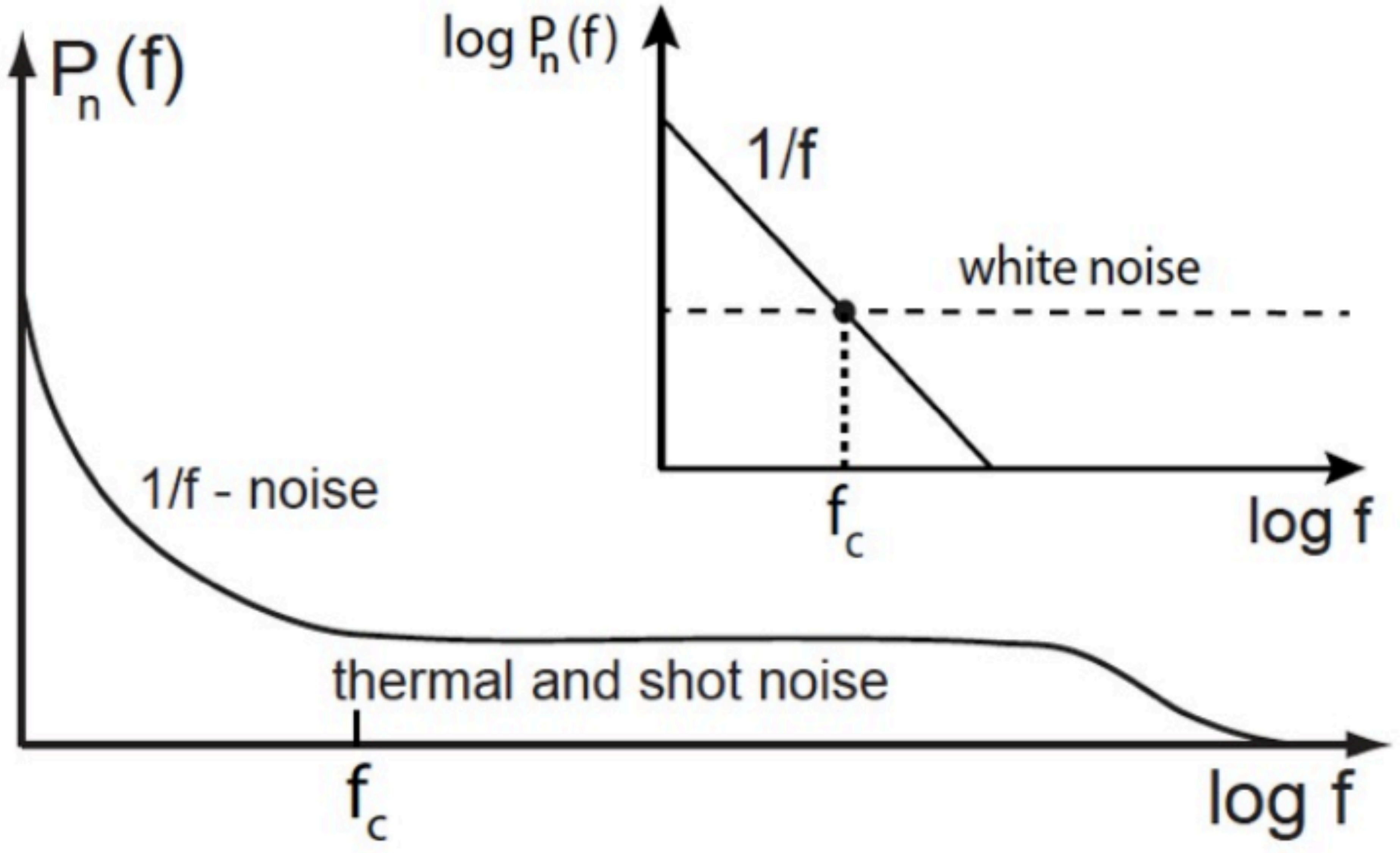
Variation around a mean value

- Noise is a variation around a mean value
  => integral over extended period = 0, characterized by variance
  Current variation $\langle i^2 \rangle$, voltage variation $\langle v^2 \rangle$



$$\sigma^2 = \langle I^2 \rangle = \lim_{T\to\infty} \frac{1}{T} \int_0^T (I(t) - I_0)^2 \, dt$$

(a) Current noise as a function of time.



(b) Spectral noise density (schematic) as a function of frequency.

f = frequency

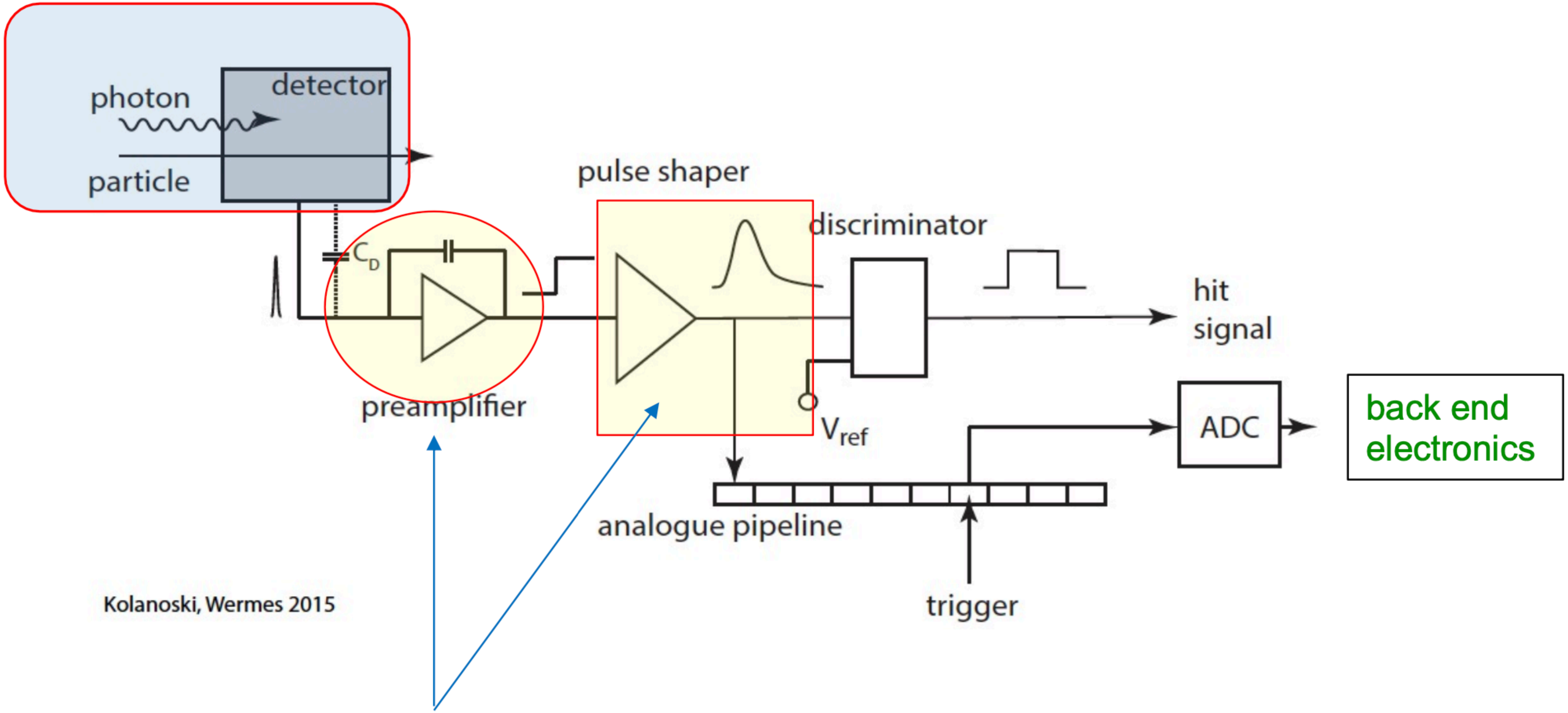
spectral noise power density:

$$\frac{dP_n}{df} = \frac{1}{R}\frac{d\left\langle v^2 \right\rangle}{df} = R\frac{d\left\langle i^2 \right\rangle}{df} \quad \Rightarrow \quad P_n = \int_0^\infty \frac{dP_n}{df} df$$

Noise Sources

Generic Detector & Readout

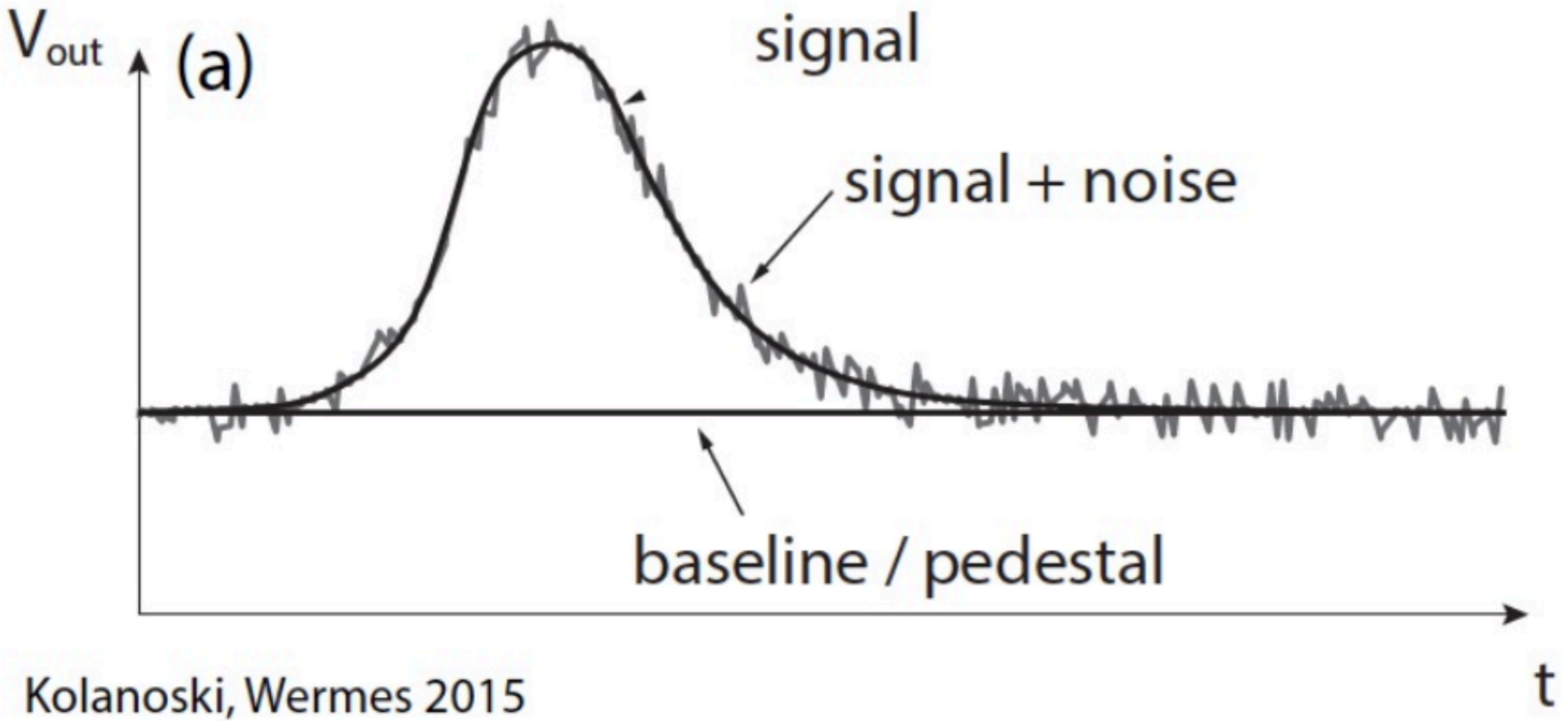
signal fluctuations electronic noise



The dominant electronic noise of a system is hidden in these parts

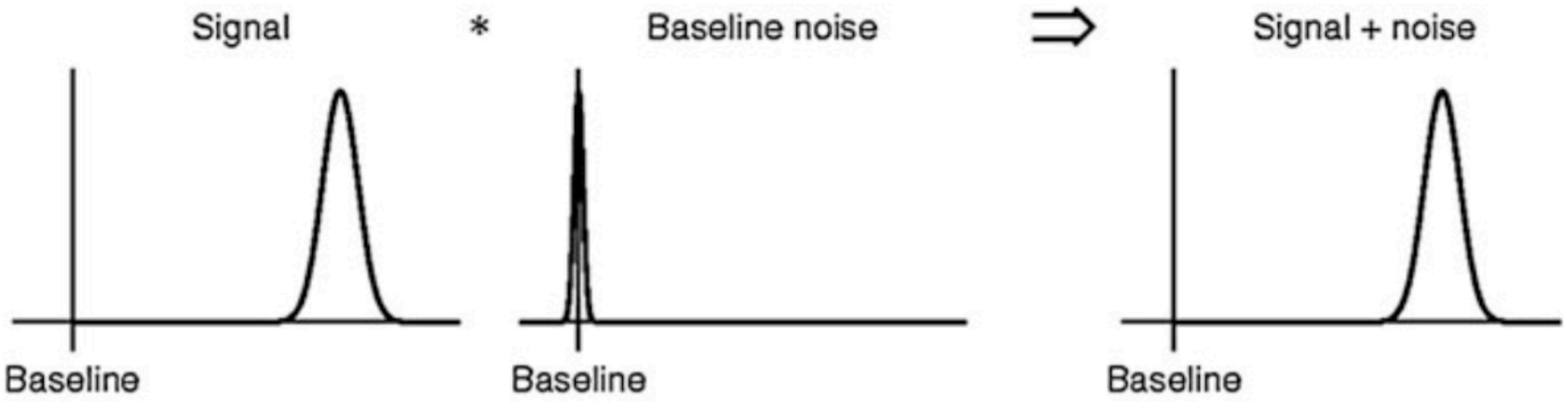
Signal Fluctuations and Electronic Noise

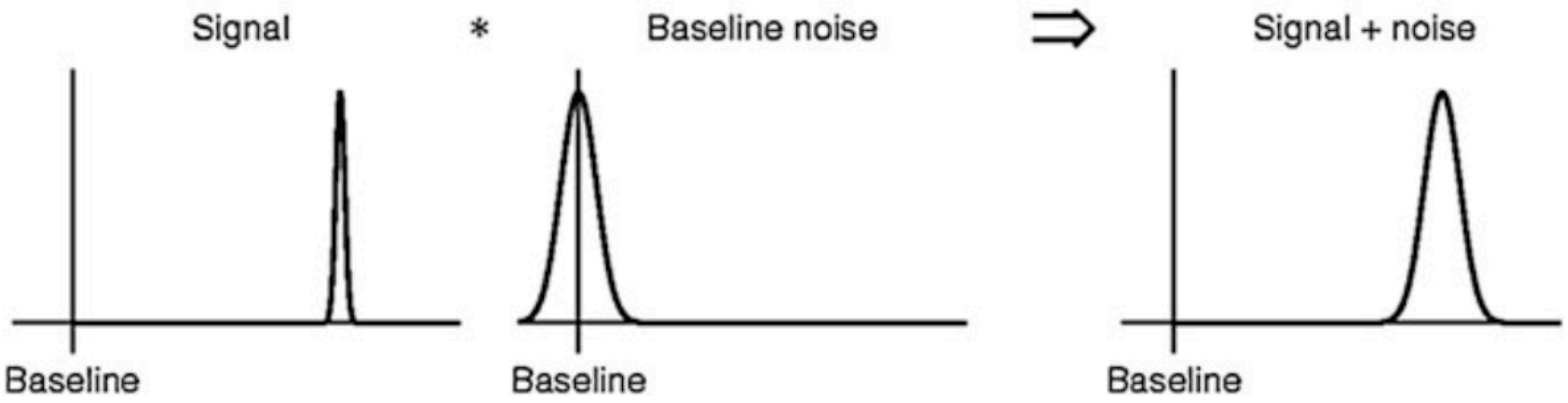
Scenarios



Kolanoski, Wermes 2015

example: scintillator with SiPM / PMT readout





example: silicon detector

Aus: H. Spieler, in I. Fleck et al. (eds.), Handbook of Particle Detection and Imaging, Springer (2020)

A current $$i = \frac{Nev}{d}$$

can fluctuate in **number**

and in in **velocity**

- fluctuations in carrier emission over a barrier
- fluctuations in trap / release processes

$$(di)^2 = \left(\frac{ev}{d} dN\right)^2 + \left(\frac{eN}{d} dv\right)^2$$

- Brownian motion (thermal)

Thermal Noise

Johnson-Nyquist Noise

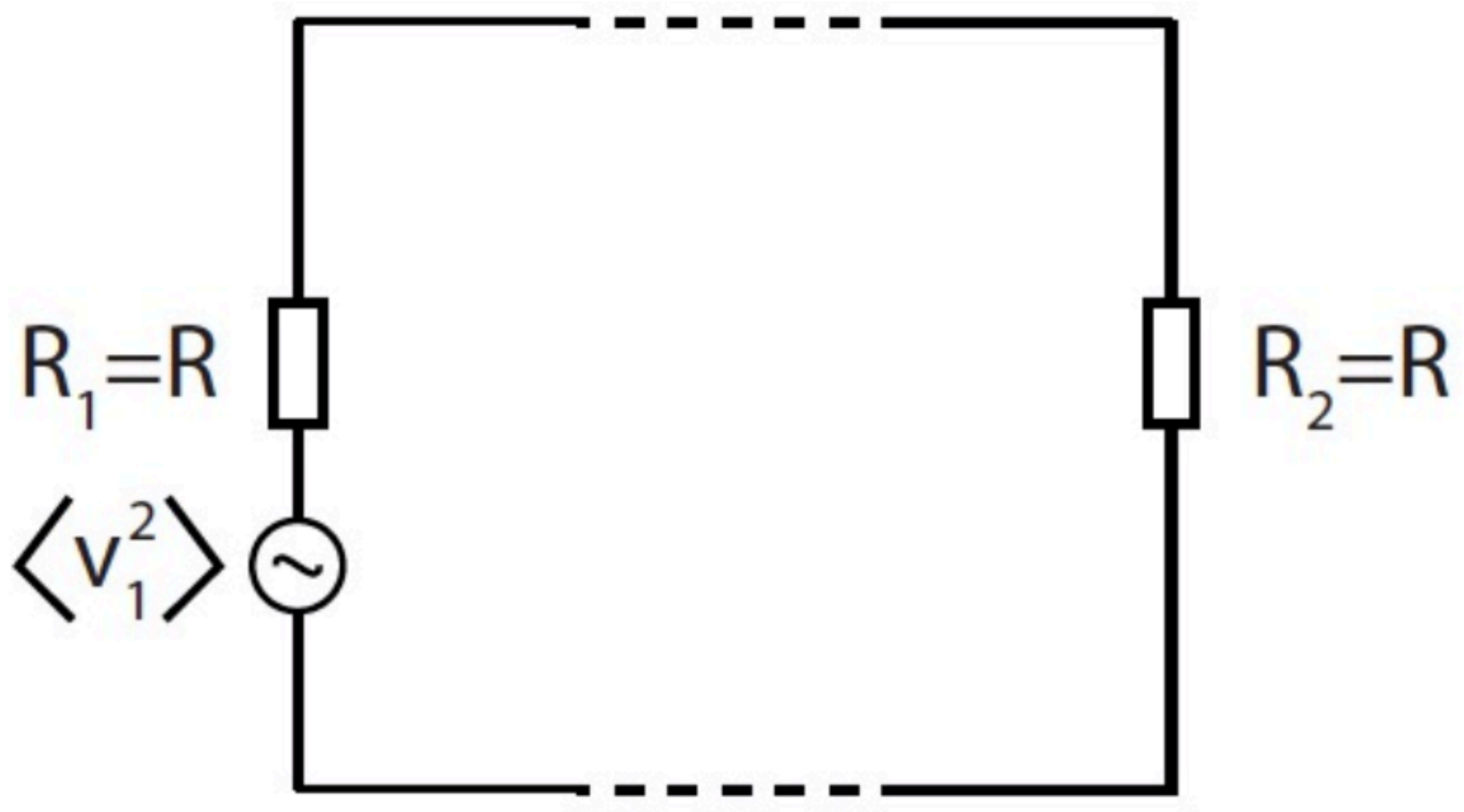
- Originates from thermal motion of charge carriers:
  Introduces current fluctuations (and with that voltage fluctuations via a resistor)

  Thermal power in equilibrium described by Planck's law:

$$\frac{dP}{d\nu} = \frac{h\nu}{exp\left(\frac{h\nu}{kT}\right) - 1} \quad \rightarrow (\text{for } h\nu \ll kT) \quad = \frac{h\nu}{1 + \frac{h\nu}{kT} - 1} = kT$$

  => Power in a frequency interval Δf independent of f: P = kT Δf "white noise"

  Thermal noise in a resistor:



Power from voltage generated by R_1 on R_2: $P_{1\text{-}2} = v^2/R$

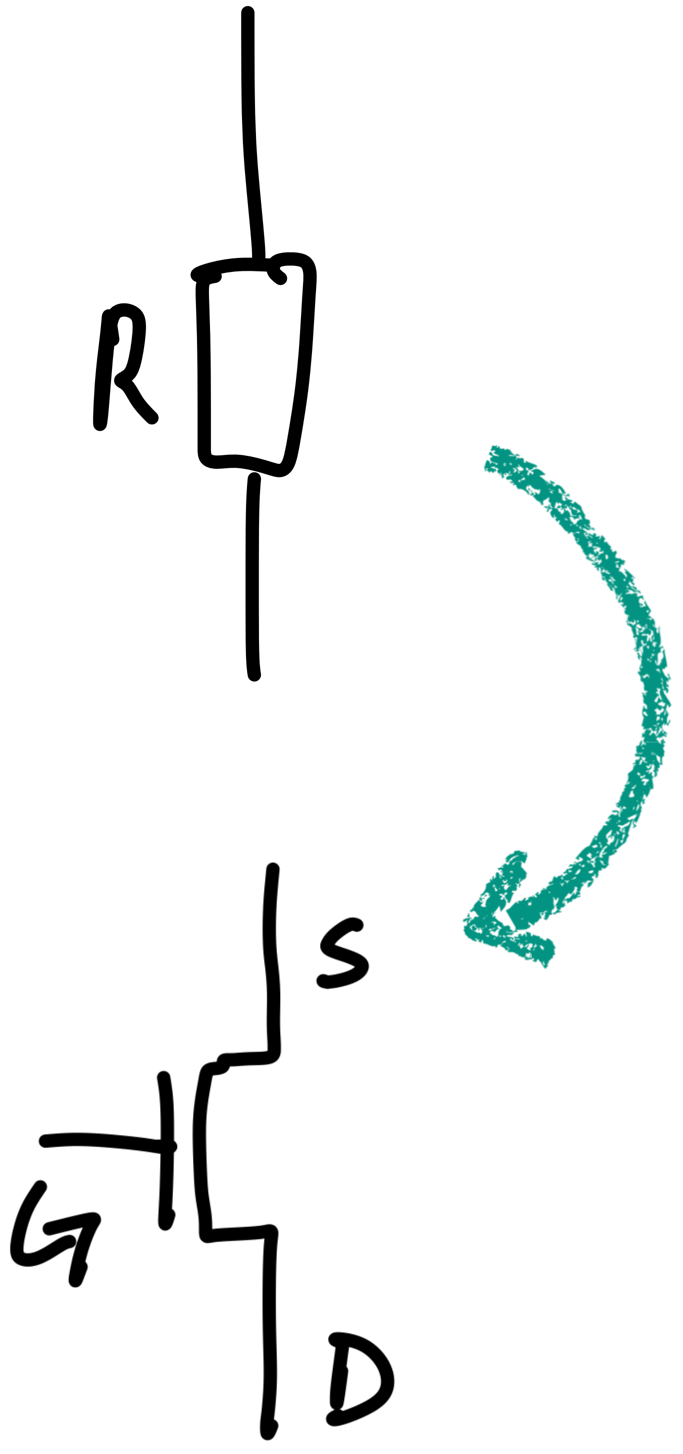
Voltage given by thermal fluctuations $\langle v_1^2 \rangle$:

$$P = \frac{\langle v_1^2 \rangle}{4R} \quad => \quad d\langle v_n^2 \rangle = 4\,kT\,R\,df \qquad d\langle i_n^2 \rangle = \frac{4\,kT}{R} df$$

Numeric example: 1 kΩ Resistor: $\sqrt{\frac{d\,\langle i^2 \rangle}{df}} = 4\frac{\text{pA}}{\sqrt{\text{Hz}}}$ or $\sqrt{\frac{d\,\langle v^2 \rangle}{df}} = 4\frac{\text{nV}}{\sqrt{\text{Hz}}}$

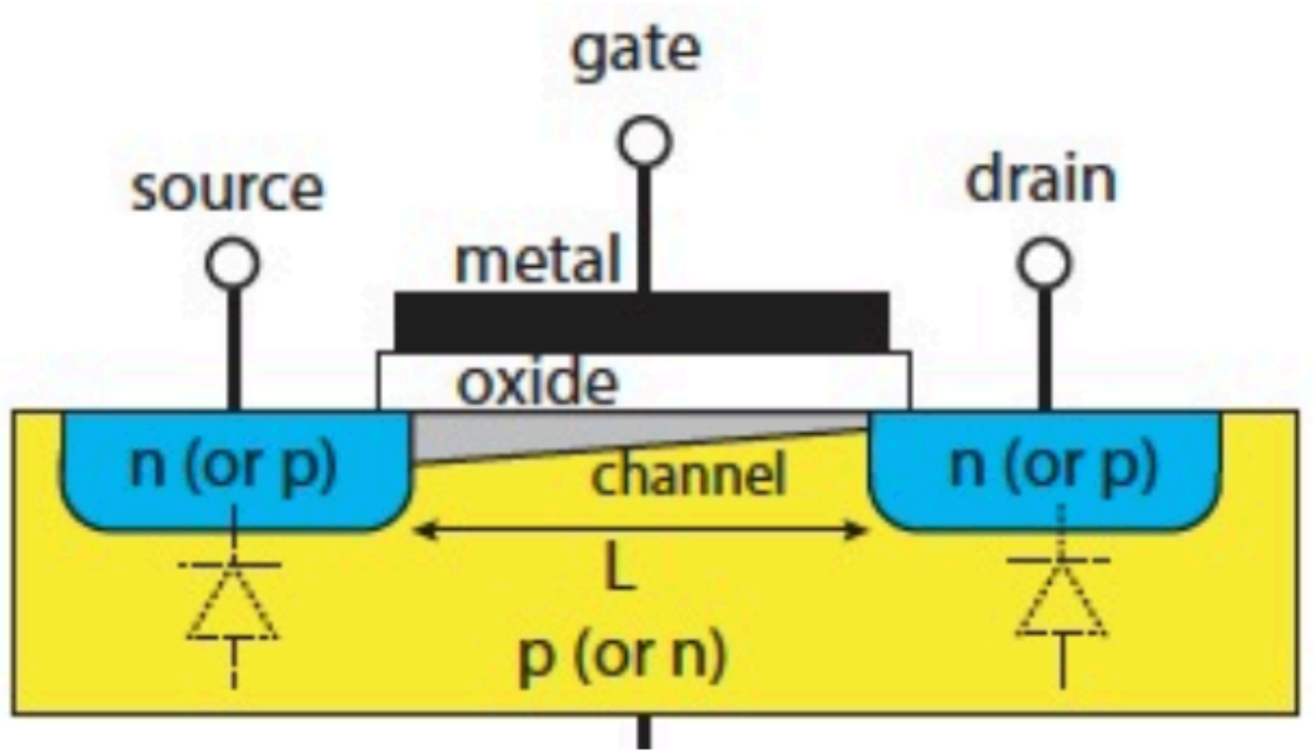
Thermal Noise

Example of a MOSFET



$$d\langle v_n^2\rangle = 4\,kT\,R\,df \qquad d\langle i_n^2\rangle = \frac{4\,kT}{R}df$$

$$d\langle v_n^2\rangle = 4\,kT\,\gamma\frac{1}{g_m}\,df \qquad d\langle i_n^2\rangle = 4\,kT\,\gamma g_m\,df$$



$$g_m = \frac{dI_{DS}}{dU_{GS}}$$

(transconductance)

γ: adjustment factor:

2/3 in strong inversion

1/3 in weak inversion

Shot Noise

Poisson Noise

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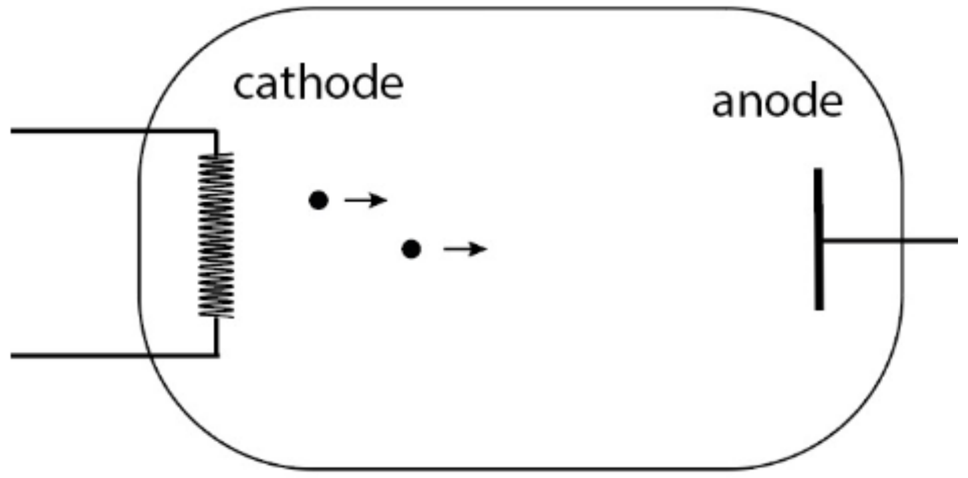
- Origin: Fluctuation of charge carrier injection in a device when quantisation plays a role
  NB: Over a barrier - NOT present in ohmic resistor

Classic example: vacuum tube



Applies equally to pn-boundaries (diodes, solid state detectors,…)
e/h in depletion zone induce *current pulses* until recombination

=> current pulses = δ functions - all frequencies contribute: white noise

$$\int_{-\infty}^{+\infty} i_e(t)dt = e$$

=> $di_e / df = 2\,e$ (convention $0 < f < \infty$ -> $-\infty < f < \infty$)

with this: noise term $$\sqrt{\frac{d < i_e^2 >}{df}} = \sqrt{2e}$$ for infinitely narrow frequency slice df

=> For a current with N electrons: average current $I = Ne/t = Ne\,\Delta f$

$$\langle i^2 \rangle = \sum_{k=1}^{N} \left(\frac{d_{i,k}}{df} \right)^2 (df)^2 = 2\,Ne^2 (df)^2 = 2e\,\underbrace{(Ne\,df)}_{\langle i \rangle}\,df = 2e\langle i \rangle df$$

needs current !?

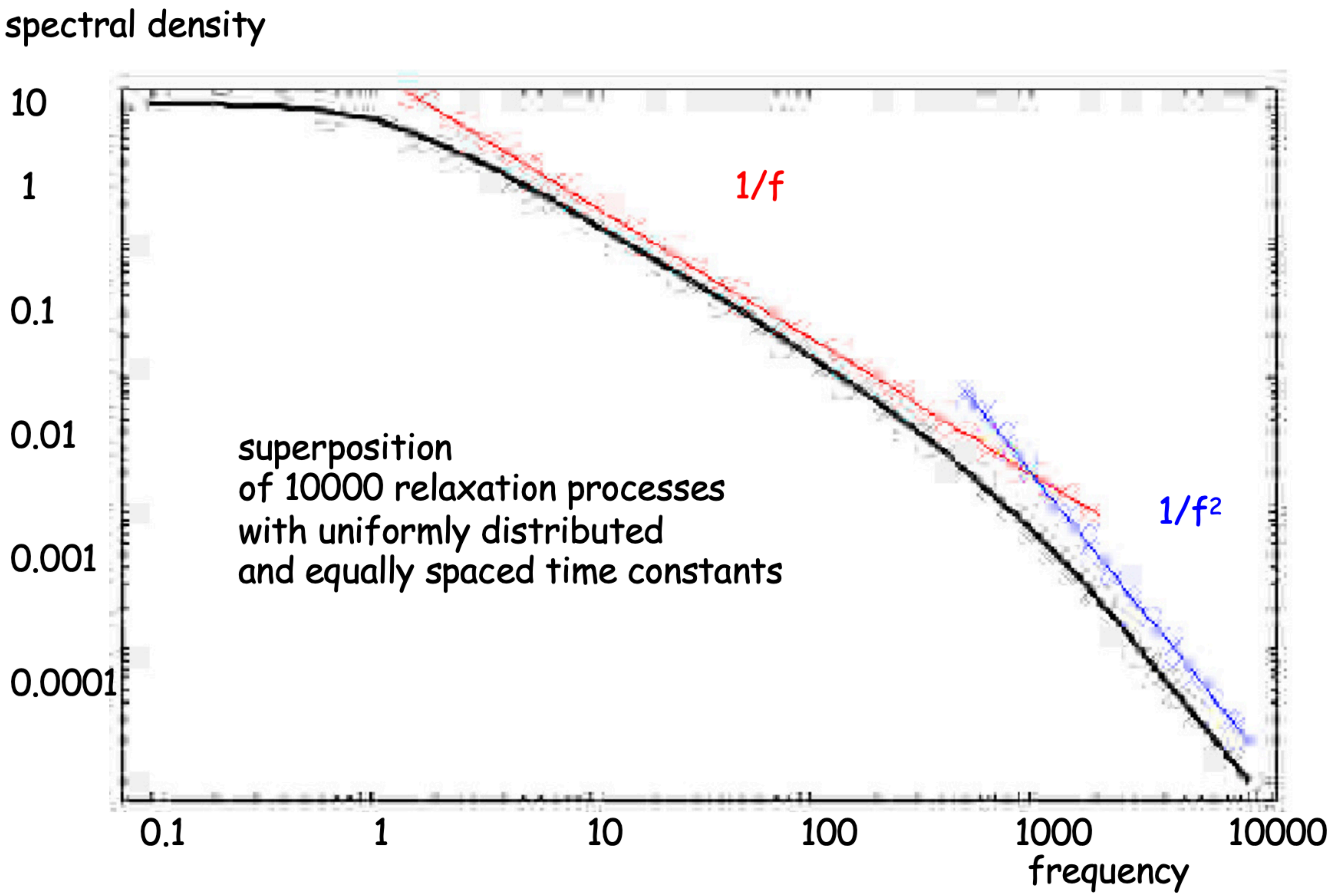
Numeric example:

1 mA current:

$$\sqrt{\frac{\Delta \langle i^2 \rangle}{\Delta f}} = \sqrt{2e\,I_0} = 18\,\frac{\mathrm{pA}}{\sqrt{\mathrm{Hz}}}$$

- Wide range of different sources - generally from a superposition of relaxation processes with different time constants.

  Results in a power spectrum that scales with 1 / (a power of f):

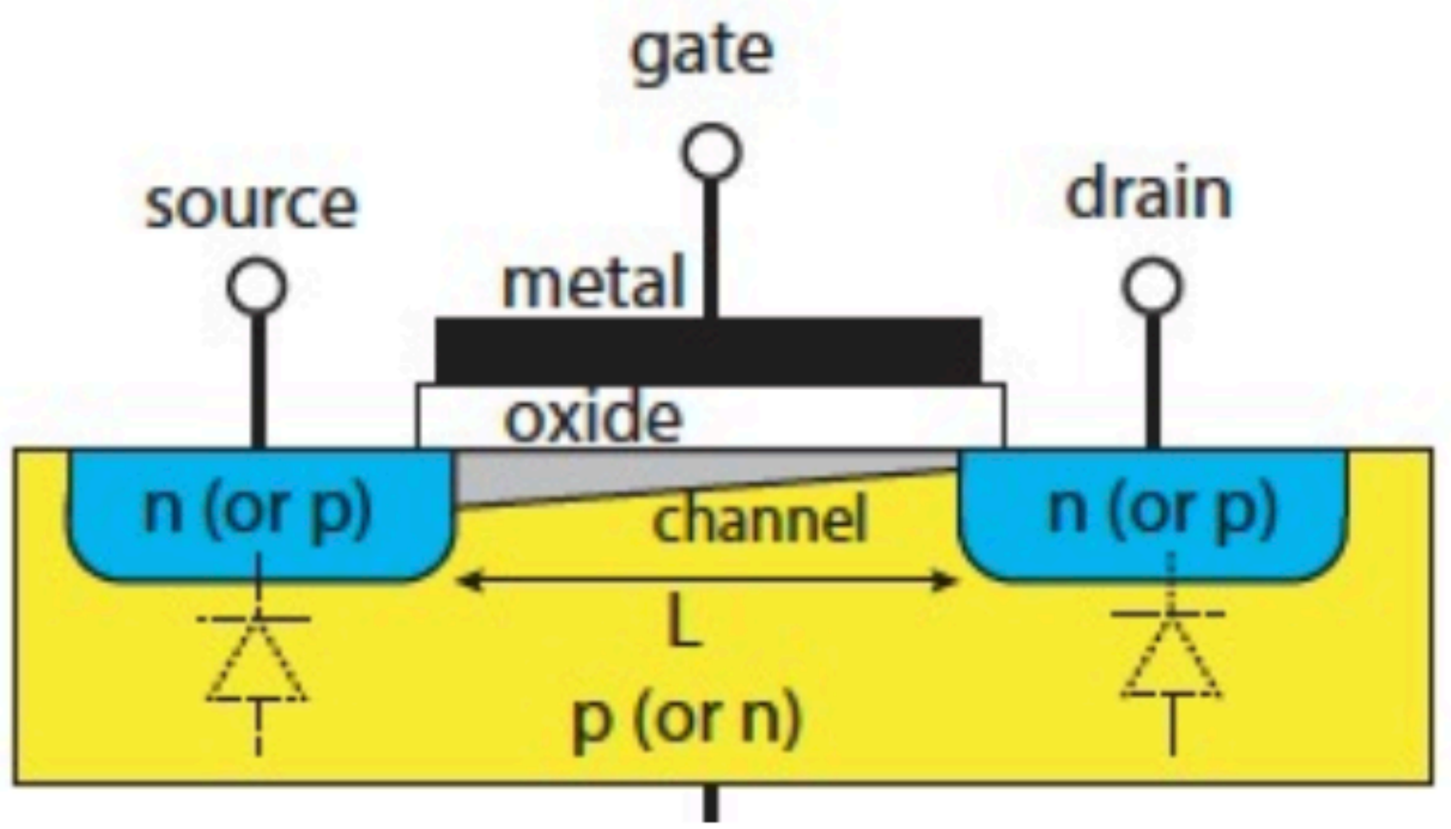


"pink noise"

arXiv:physics/0204033

1/f Noise

Example: MOSFET



- Originates from trapping and release of charges in gate oxide
    - depends on gate area A = W x L

$$\frac{d\left\langle v_{1/f}^2\right\rangle}{df} = K_f \frac{1}{C'_{ox} W L}\frac{1}{f}$$

empirical parametrisation (e.g. PSPICE)

$$C'_{ox} = \frac{3}{2}\frac{C_{GS}}{WL} \approx \epsilon_0\epsilon/d$$

$K_f^{NMOS} \approx 30 \times 10^{-25}$ J, $K_f^{PMOS} \approx 0.05\text{-}0.1 \times K_f^{NMOS}$

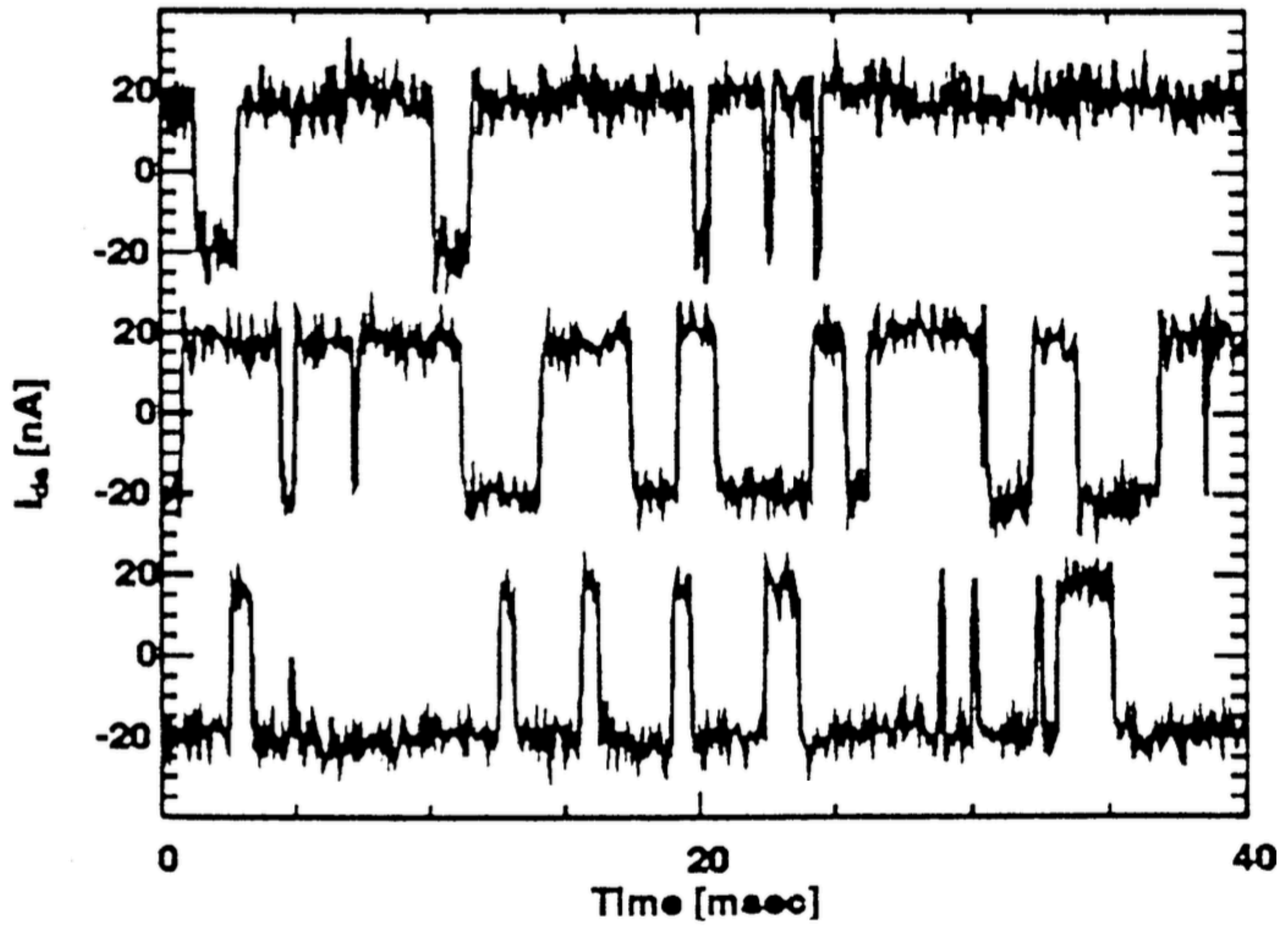
- One source of 1/f noise

RTS noise: Random Telegraph Signal noise
also: “burst noise”, “popcorn noise”

Usually related to trapping/detrapping processes.

Superposition of several different processes with different trapping time results in a 1/f contribution.

Typically low frequency: Hard to filter out, can be a significant challenge for low-noise devices.



Noise Sources - Summary

Three main drivers

$$\langle i^2 \rangle = \frac{4\,kT}{R} df$$

thermal fluctuations (Brownian motion)

velocity fluctuations

thermal noise

(in resistors, transistor channels)

$$\langle i^2 \rangle = 2e\langle i \rangle df$$

fluctuations in hopping over a barrier (shot)

number fluctuations

shot noise

(where currents due to barrier crossings appear, e.g. in diodes, NOT in resistors)

$$\langle i^2 \rangle = const\ \frac{1}{f^\alpha} df$$

trap/release fluctuations of carriers

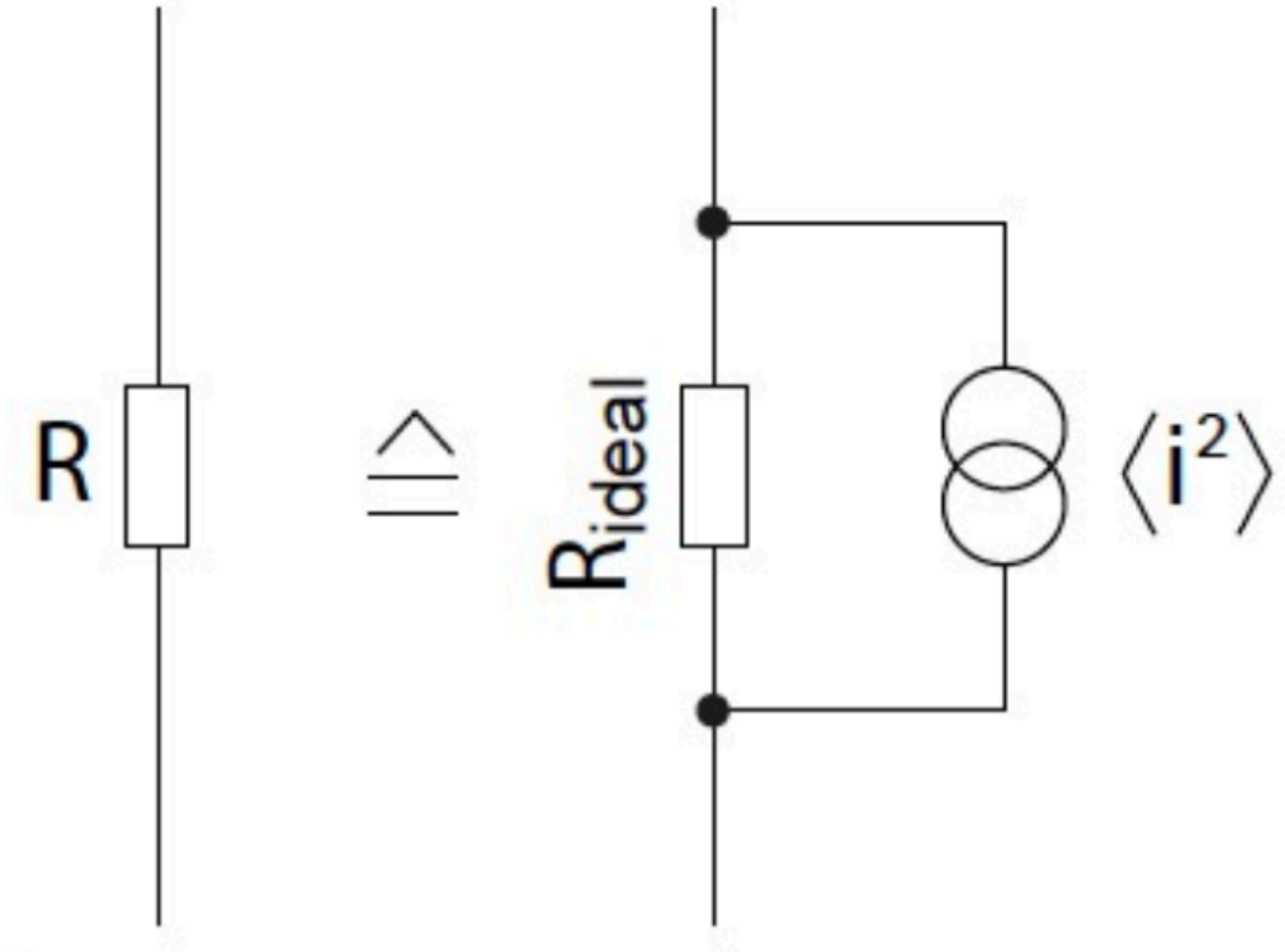
number fluctuations

1/f noise

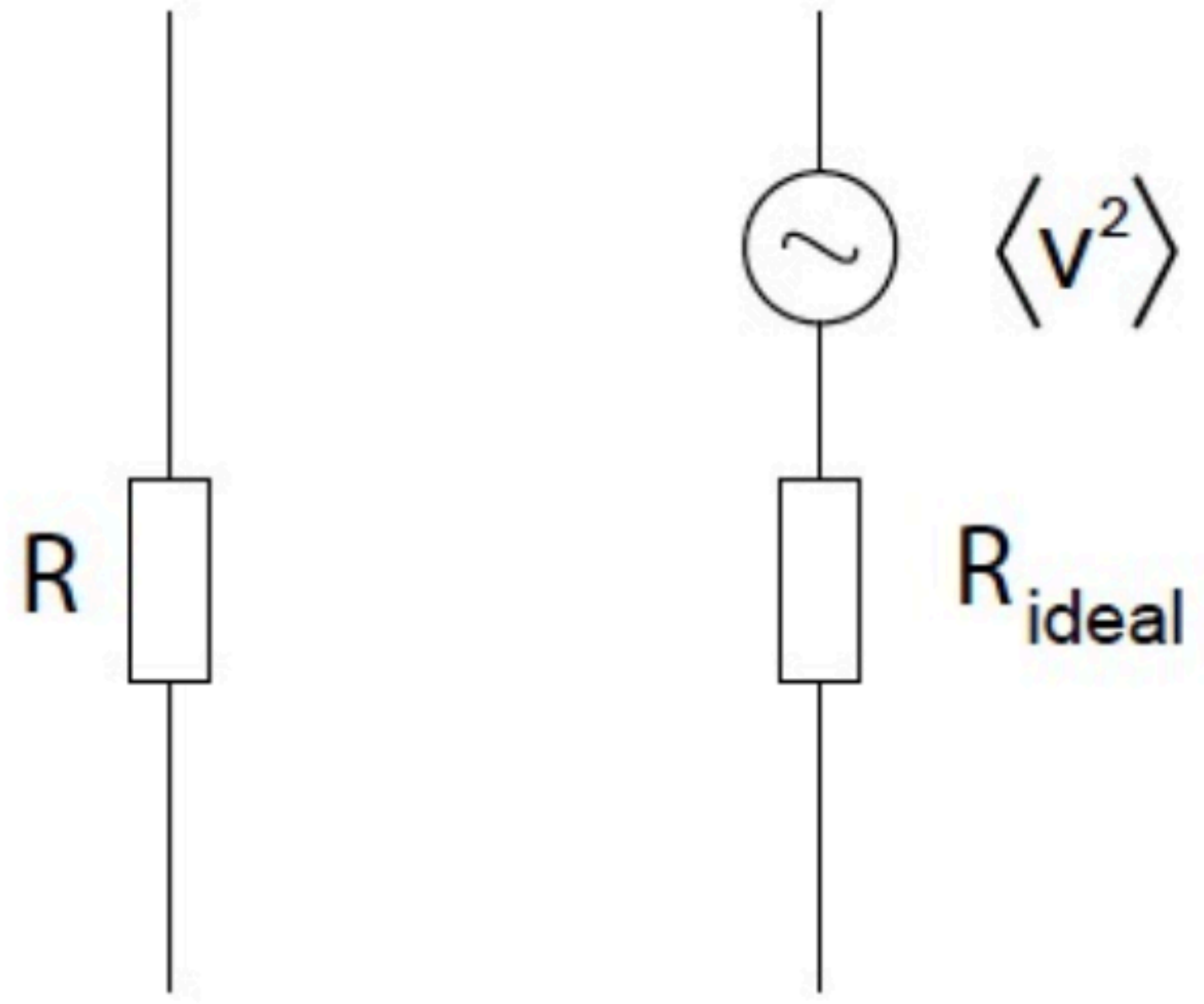
(whenever trapping occurs,
e.g. in (MOS) transistor channels)

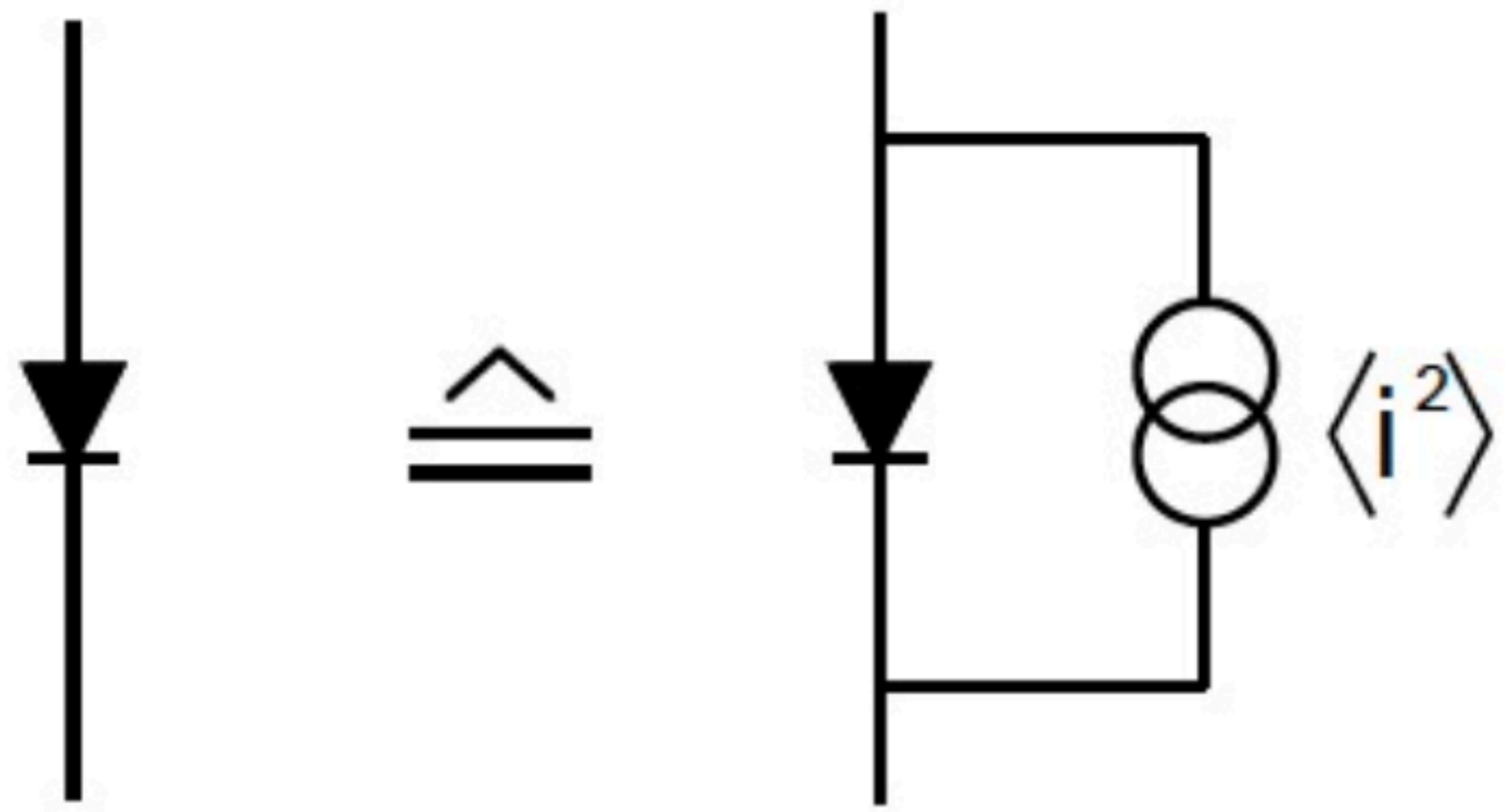
Describing Noisy Circuit Elements

Replacement Circuits



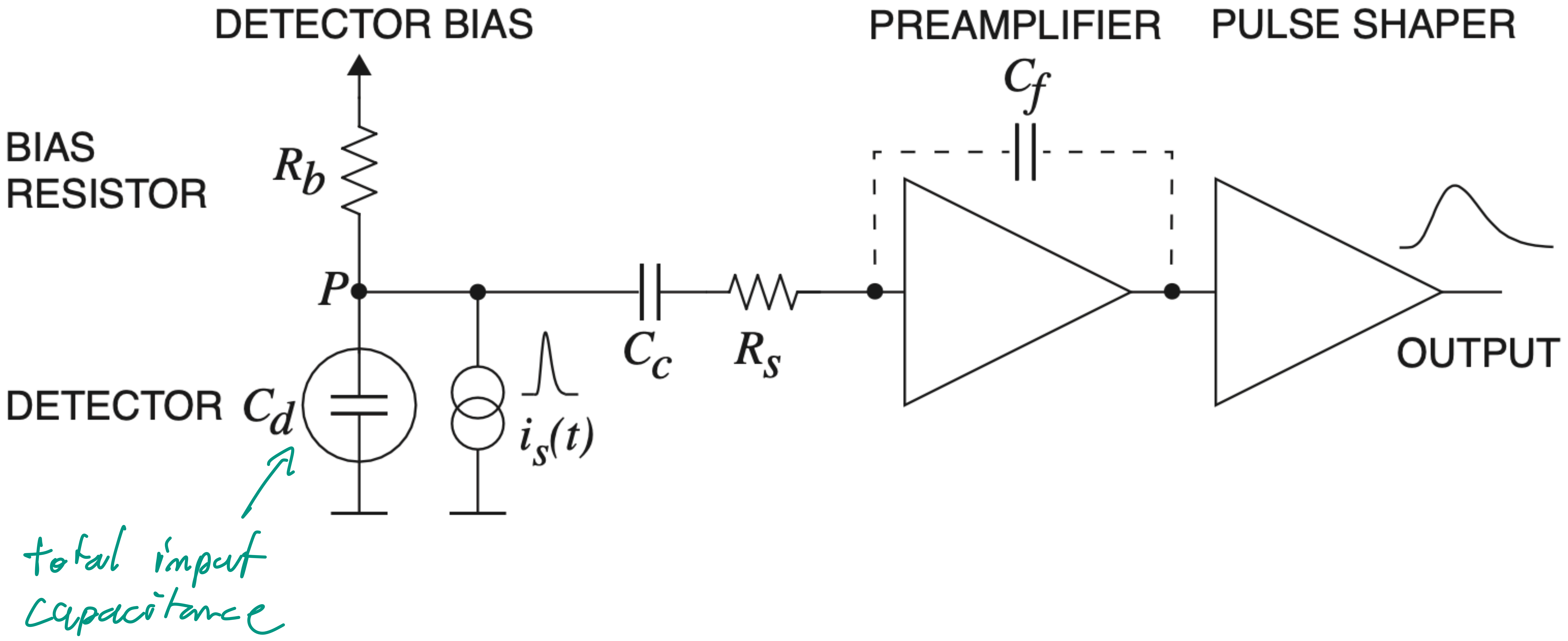
current
or
voltage





Which Noise Source Contributes Where?

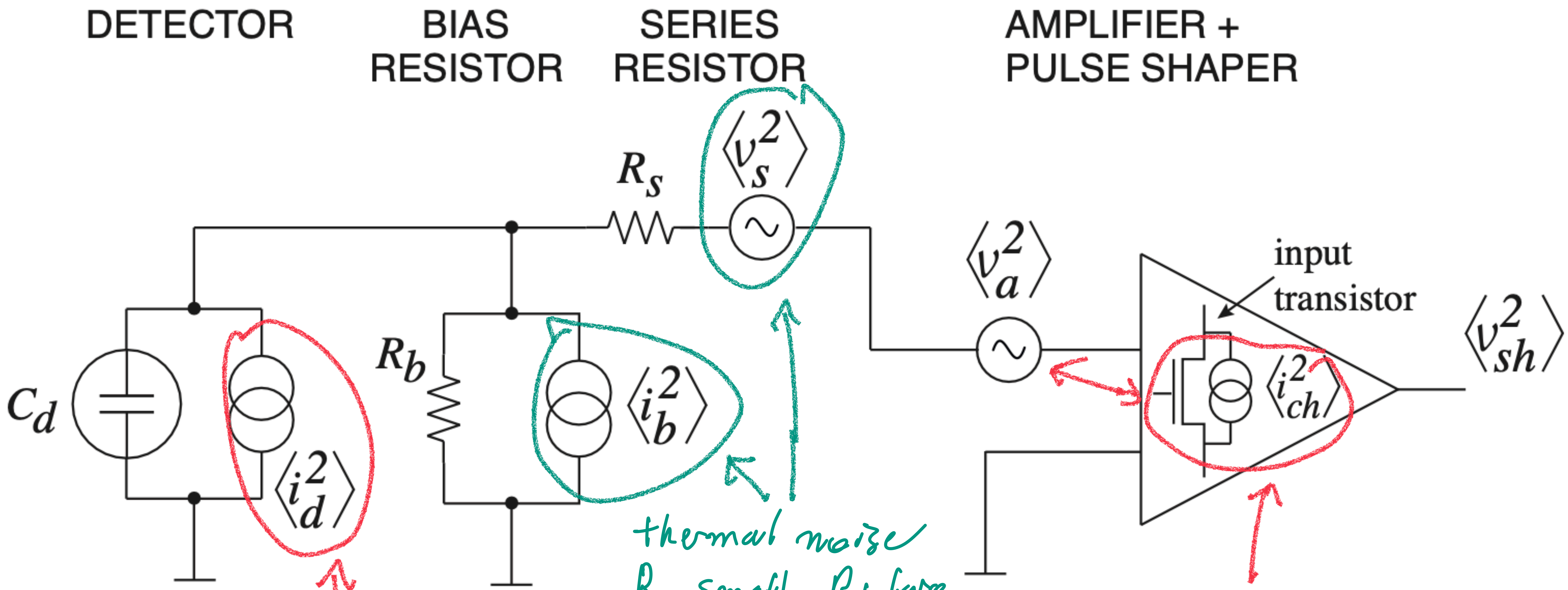
Back to the Detectors



from: R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

Which Noise Source Contributes Where?

Replacement diagram for noise analysis



thermal noise
R_s small, R_b large:
⇒ typ. negligible

shot noise from detector (leakage) current

$$d\langle i_d^2 \rangle = 2e\, I_d\, df$$

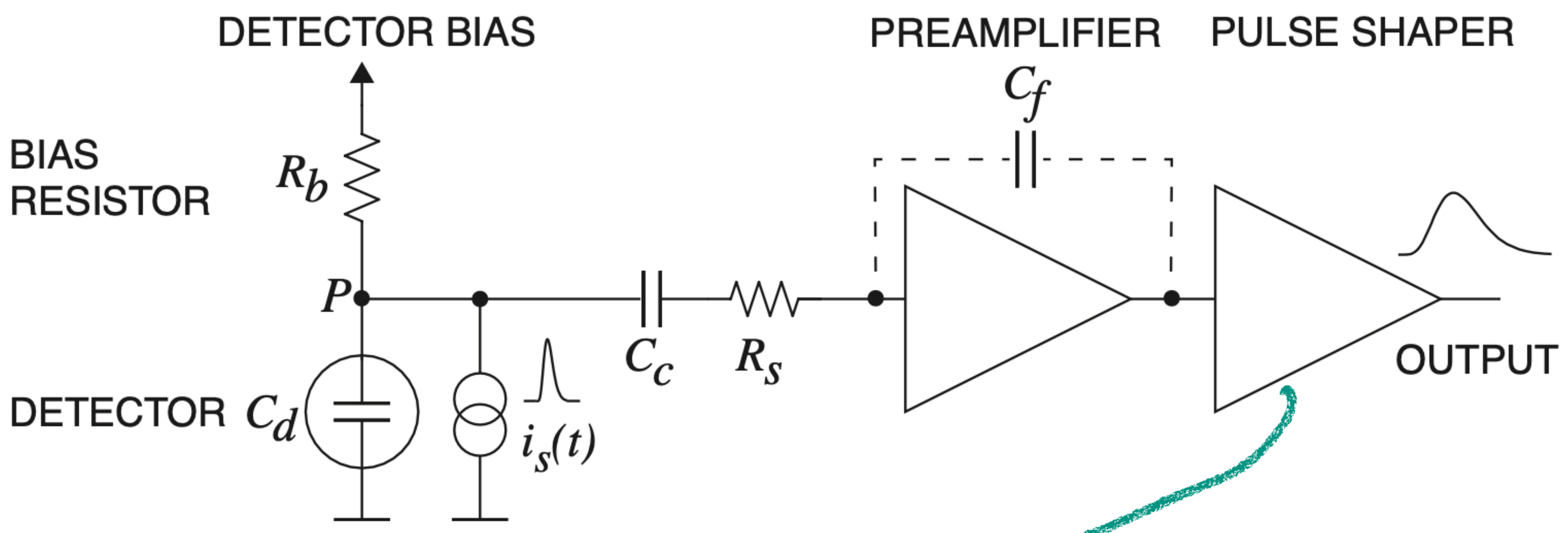
noise in amplifier channel

thermal $\quad d\langle i^2 \rangle = 4\, kT \gamma g_m\, df$

1/f $\quad d\langle i^2 \rangle = K_\alpha \frac{1}{f^\alpha} df$

from: R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

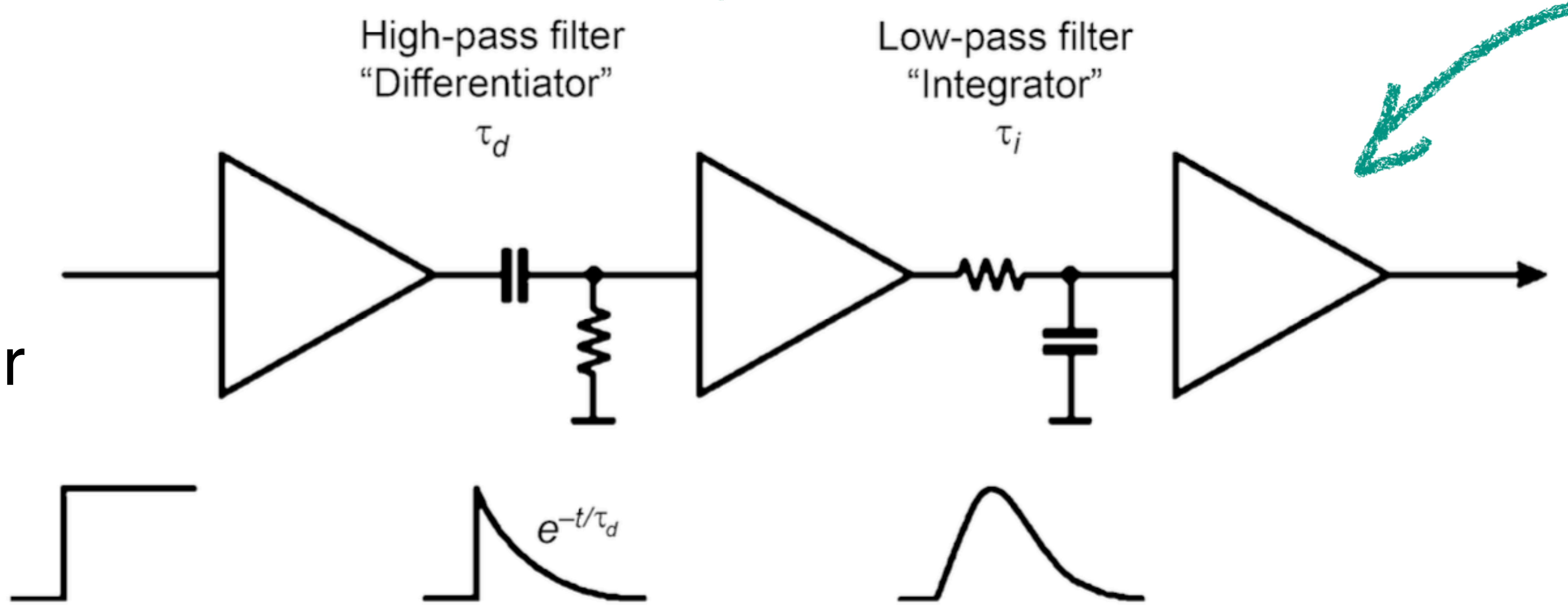
How Filters Influence Noise Effects

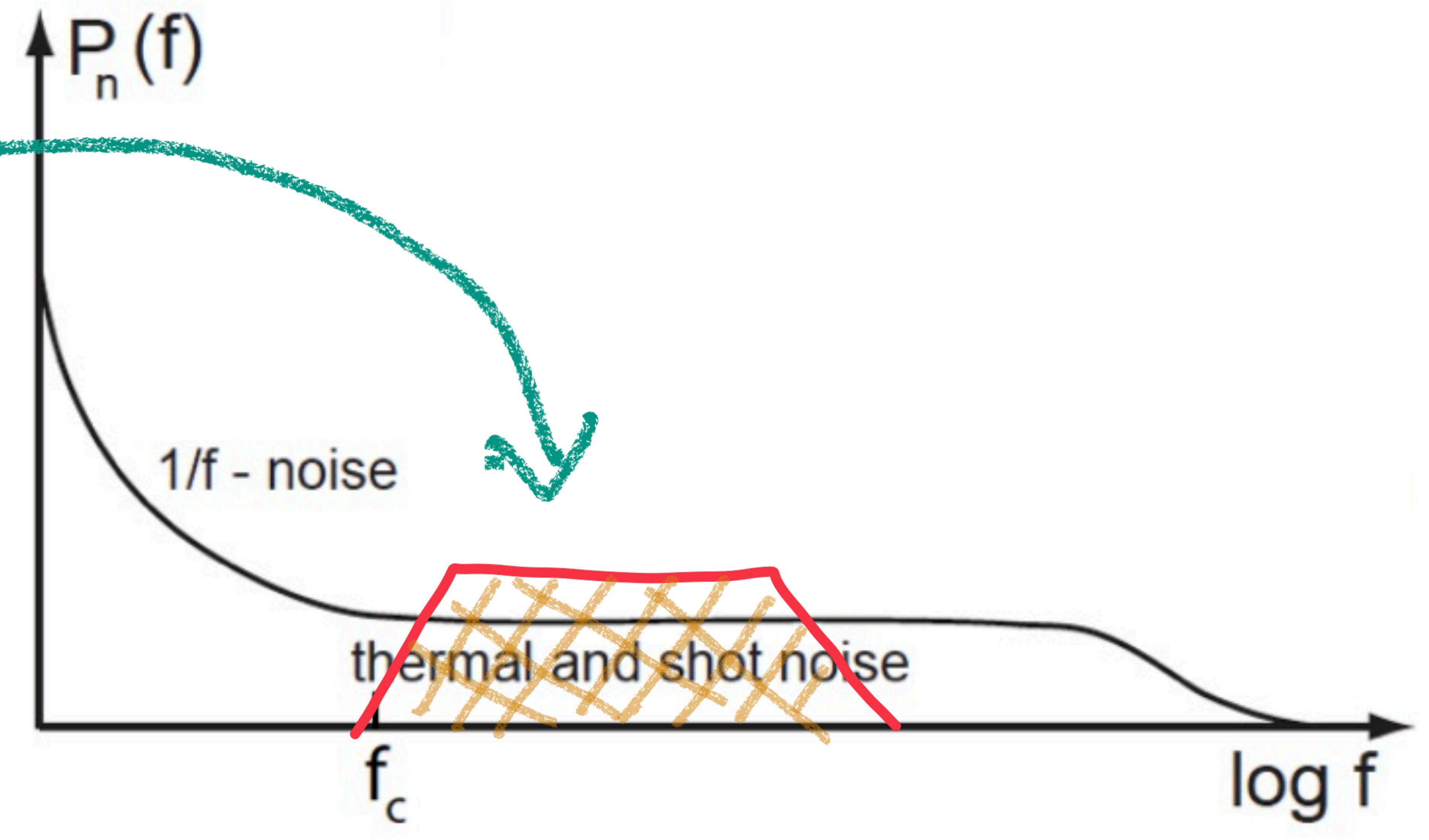


Shaper: A Bandpass
shaping time τ
(larger τ = smaller bandwidth)

Simple shaper: CRRC

from preamp:
current integrator





Equivalent Noise Charge

Quantifying Detector System Noise

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- Understanding the noise performance of a system: Expressing the noise in signal units
  "How many electrons as signal would produce the noise voltage output behind the shaper?"

$$\mathrm{ENC} = \frac{\text{noise output voltage [V]}}{\text{output signal of a signal of 1 } e^- \; [\mathrm{V}/e^-]}$$

$$\mathrm{ENC}^2 = \frac{\langle v_{sh}^2 \rangle}{v_{sig}^2}$$

$$\mathrm{ENC}^2\,(e^{-2}) = \frac{(2.71)^2}{4e^2}\left(eI_d\tau + 2C_D^2\,K_f \frac{1}{C'_{ox}WL} + \gamma \frac{2kT}{g_m}\frac{C_D^2}{\tau} \right)$$

[w/o derivation]

$$= a_{\mathrm{shot}}\,\tau + a_{1/\mathrm{f}}\,C_D^2 + a_{\mathrm{therm}}\frac{C_D^2}{\tau}\,,$$

$$\mathrm{ENC}^2\,(e^{-2}) = 11\,\frac{I_d}{\mathrm{nA}}\,\frac{\tau}{\mathrm{ns}} + 740\,\frac{1}{WL/(\mu\mathrm{m}^2)}\,\frac{C_D^2}{(100\,\mathrm{fF})^2} + 4000\,\frac{1}{g_m/\mathrm{mS}}\,\frac{C_D^2/(100\,\mathrm{fF})^2}{\tau/\mathrm{ns}}$$

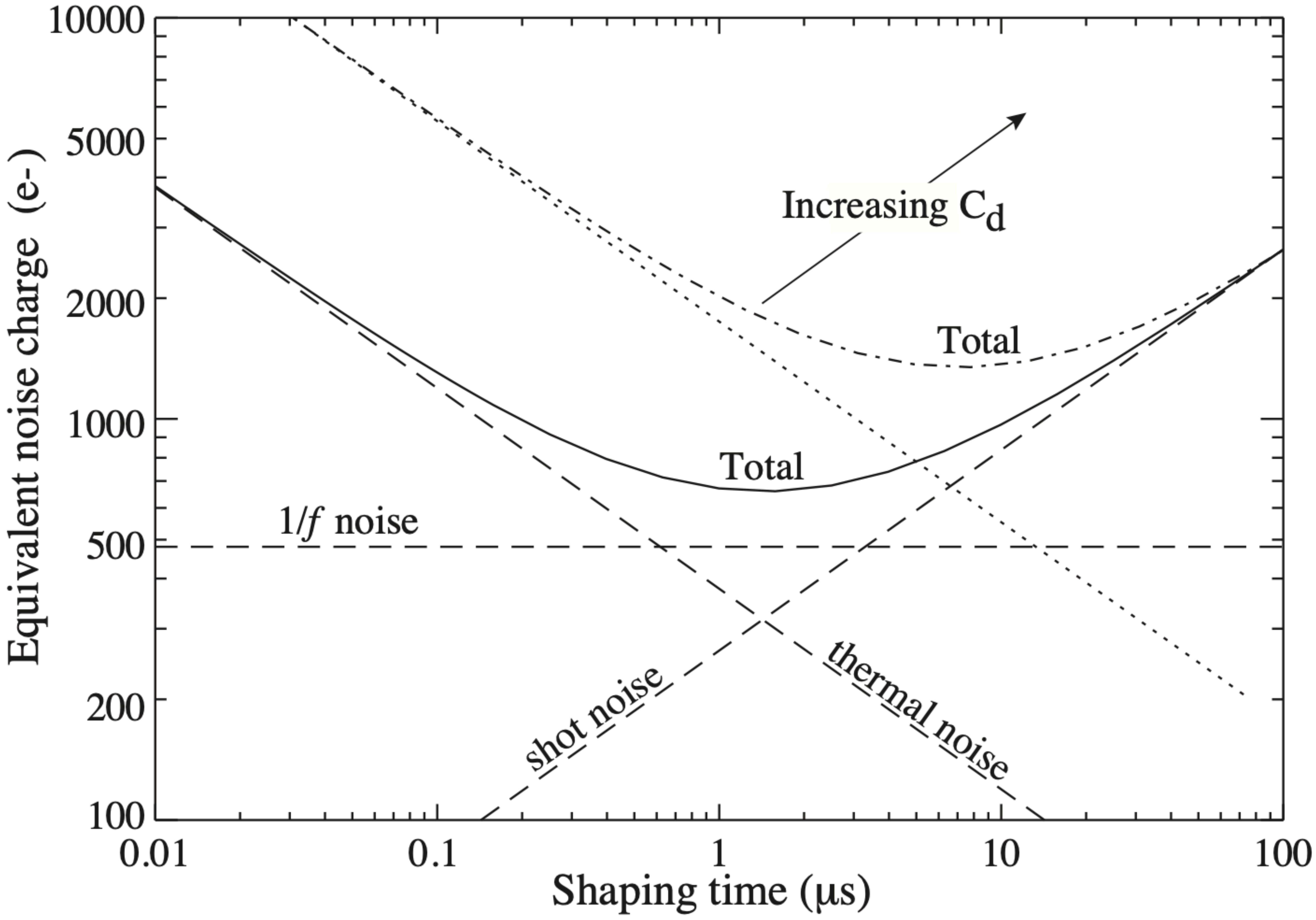
leakage current shaping time input capacitance shaping time

with: $\gamma = 2/3,\ K_f = 33 \times 10^{-25}\mathrm{J}$, and $C'_{ox} = 6\ \mathrm{fF}/\mu\mathrm{m}^2$

from: R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

Optimal Filters

Selecting the right shaping time



- shaping time can be optimized to obtain the smallest possible ENC for a given combination of noise contributions.

Examples for realistic systems

Equivalent noise charge

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35.9.2.0.1 Examples Using (35.36) one finds for a typical pixel detector (before heavy irradiation) with $C_D = 200\,\mathrm{fF}$, $I_d = 1\,\mathrm{nA}$, $\tau = 50\,\mathrm{ns}$, $W = 20\,\mu\mathrm{m}$, $L = 0.5\,\mu\mathrm{m}$, $g_m = 0.5\,\mathrm{mS}$:

$$\mathrm{ENC}^2 \approx (24\,e^-)^2\Big|_{\mathrm{shot}} + (17\,e^-)^2\Big|_{1/\mathrm{f}} + (25\,e^-)^2\Big|_{\mathrm{therm}} \approx (40\,e^-)^2 .$$

For a typical silicon microstrip detector after radiation damage (fluence $\gtrsim 10^{14}\mathrm{n_{eq}/cm^2}$, assuming no degradation of the front-end electronics due to radiation) one obtains for $C_D = 20\,\mathrm{pF}$, $I_d = 1\,\mu\mathrm{A}$, $\tau = 50\,\mathrm{ns}$, $W = 2000\,\mu\mathrm{m}$, $L = 0.4\,\mu\mathrm{m}$, $g_m = 5\,\mathrm{mS}$:

$$\mathrm{ENC}^2 \approx (750\,e^-)^2\Big|_{\mathrm{shot}} + (200\,e^-)^2\Big|_{1/\mathrm{f}} + (800\,e^-)^2\Big|_{\mathrm{therm}} \approx (1100\,e^-)^2 .$$

Apart from the larger leakage current, the larger capacitance of strips compared to pixels leads to a much worse noise performance which can only be partially compensated by allowing more power in the amplification transistor, *i.e.*, by increasing g_m.

A liquid argon calorimeter cell is a suitable example of a detector with a large electrode capacitance with typical parameters (similar to the ATLAS central electromagnetic calorimeter, see Sec. 35.10). Using $C_D = 1.5\,\mathrm{nF}$, $I_d = <2\,\mu\mathrm{A}$, $\tau = 50\,\mathrm{ns}$, $W = 3000\,\mu\mathrm{m}$, $L = 0.25\,\mu\mathrm{m}$, $g_m = 100\,\mathrm{mS}$, one obtains:

$$\mathrm{ENC}^2 \approx (1000\,e^-)^2\Big|_{\mathrm{shot}} + (15000\,e^-)^2\Big|_{1/\mathrm{f}} + (13500\,e^-)^2\Big|_{\mathrm{therm}} \approx (20200\,e^-)^2 .$$

Here only a small (negligible) parallel shot noise (leakage current) contribution is assumed, which is typical for liquid argon calorimeters.

aus: N. Wermes in R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

DONE!

Thank you all for your participation.

If you are interested in HiWi positions or a thesis on "technical" topics in physics please get in touch!

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KIT, Winter 2023/24

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